# Design & Analysis of Low Vision Accessibility Tools For the Metaverse

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## Abstract

The field of Virtual Reality is a rapidly growing and increasingly popular medium, however, the accessibility standards for individuals with low vision in VR have not yet been fully established, leaving a significant gap in the provision of accessible VR experiences for individuals with low vision. The objective of this study was to investigate the effectiveness and efficiency of accessibility tools for people with low vision in virtual reality by leveraging the 3D modality of VR. Six volunteers participated in the study, three of whom had low vision. The study utilised a virtual environment created in Unity, in which participants were tasked with completing 9 tests in 3 or 4 different ways depending on their vision: once without the use of any accessibility tools, and three more times using different accessibility tools. The study used 3 different types of accessibility tools: a right-hand magnifier, a left-hand magnifier, and a SeeingVR magnifier. The results of the study indicate that the magnifier tools were a huge help for the participants with low vision in completing the tasks, and reduced the cognitive load during the execution of the task.

Keywords: Metaverse, Virtual Reality, Unity, 3D, HCI, UX, Accessibility, Low Vision

# Contents

# Background of the Study

Virtual Reality is a newly popularised and rapidly growing computer platform. Due to its novelty the accessibility standards nor the accessibility tools have been created or standardised yet. According to WHO approximately 3.5% of world's population (284 million) consists of people who are visually impaired and 0.5% (39 million) are legally blind with varying levels of residual/remaining visual acuity (VA) (Koyuncular, 2021). Like more established computing platforms web, desktop, mobile … etc. there is need for accessibility tools for VR platforms as well. However due to the 3D nature of this platform pre established tools do not directly translate over. There might be more efficient ways of making these platforms more accessible while leveraging the 3D modality of the platform.

Initially, we were aware of a lack of accessibility tools in VR, and were contemplating on whether it would be beneficial to try developing an accessibility tool ourselves. During the literature review phase of the project, we have discovered various different accessibility prototypes and papers on their effectiveness. Their results indicated that accessibility tools in VR were indeed beneficial for people with low vision and that we can improve them by focusing on the interactive and 3D aspects of VR. Using these findings, we have developed a novel accessibility tool with people with low vision as our target group, and tested the efficiency, effectiveness and satisfaction of our tool.

## Related Literature

**SeeingVR:** SeeingVR is essentially a set of tools designed to improve the accessibility of virtual reality applications for users with low vision. They conducted a study to identify the challenges faced by users with low vision in VR. SeeingVR includes 14 tools that can be used to augment a VR application with visual and audio feedback. They conducted a study with 11 participants with low vision to evaluate the effectiveness of SeeingVR in improving the VR experience for users with low vision. The study involved a tutorial, a virtual task session, and an app experience session. The virtual task session included three tasks: menu navigation, visual search, and target shooting. Authors also tested the robustness of SeeingVR plugin with 10 popular VR apps, and evaluated the usability of the Unity toolkit with six developers. Authors concluded that their 14 accessibility tools helped people with low vision complete tasks in VR more quickly and accurately. Furthermore, they have concluded that these accessibility tools made VR more enjoyable for people with low vision. They have also discussed that even though accessibility guidelines for 2D media are matured, currently there are no VR-specific guidelines for accessibility and the space of accessibility is underexplored, and that their work has the potential to inspire the development of general accessibility standards for VR (Zhao et al., 2019).

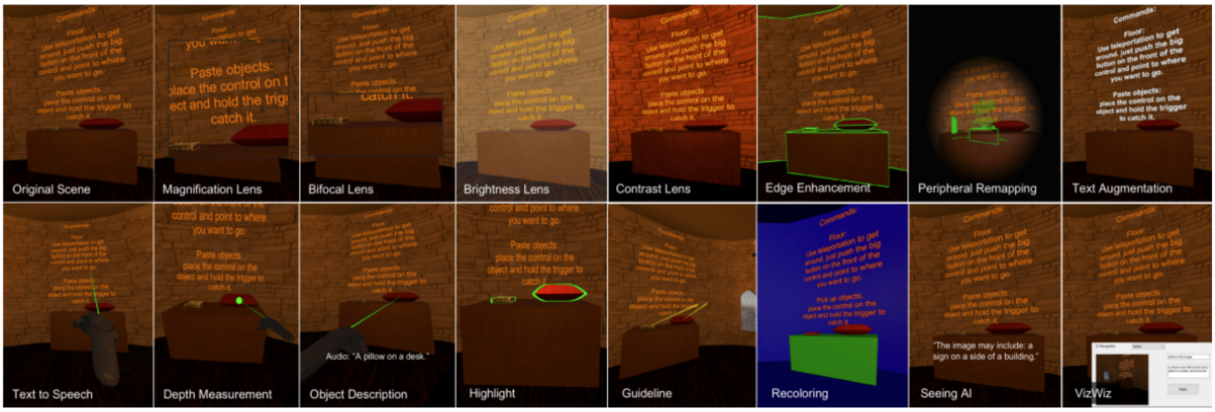


Figure 1-1: Accessibility Tools Developed by SeeingVR

**CLEVR**: This study investigates the usefulness and adaptability of a virtual reality application the research team has developed, called CLEVR, for people with low vision. The researchers designed and implemented an interaction interface based on user and expert feedback, and evaluated it in a user study with 18 unpaid participants with low vision. The participants completed four tasks using CLEVR and then on a desktop computer for comparison. The tasks were intended to be representative of tasks that people would have to do regularly. The results of the study showed that 13 out of 18 participants were able to complete all tasks efficiently using CLEVR, demonstrating that VR accessibility tools have the potential to aid people with low vision. The participants also reported that the revised interaction system was more suitable and provided reliable control over regular aids and screens. However, 17 out of 18 participants indicated that using CLEVR was more demanding than using a desktop computer in terms of physical and mental strain. The results of this study suggest that VR can be a suitable aid to support the individual needs of people with low vision (Hoppe et al., 2020).


Figure 1-2: Accessibility Tools Developed by CLEVR

**<u>Accessible News Reading</u>:** This research aims to explore the potential of virtual reality as a platform for accessible news reading for individuals with low vision. The authors review the current state of low-vision reading aids, including print, digital devices, and audio, and highlight the limitations of these solutions for news reading regarding individuals with low vision. They then argue that VR has unique advantages as a reading platform for low vision, including comfort, mobility, wide visual field of view, multifunctionality, multimedia capabilities, and interactivity. Based on this, the authors propose a set of different design principles and a demo for VR reading applications, such as adjustable print and text layouts, smart text contrasting, an accessibility menu, image enhancement... In conclusion, the authors argue that VR has the potential to be an effective platform for accessible news reading for low vision and argue that further research should be conducted to better utilise what this medium has to offer (Wu et al., 2019).

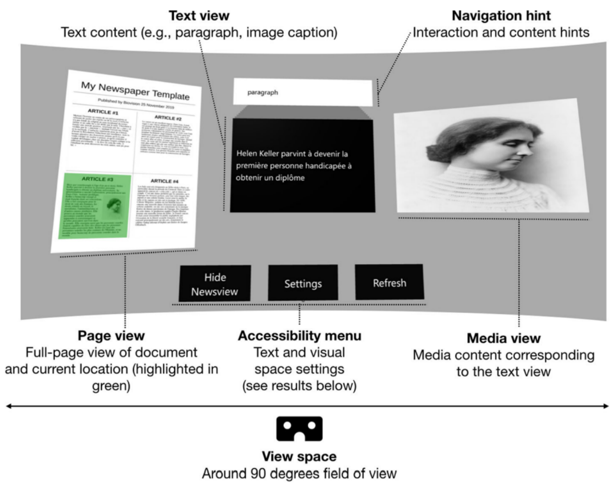


Figure 1-3: Accessibility Tools Developed by Accessible News Reading Team

The current study was conducted to evaluate the effect of leveraging the 3D nature of the Metaverse and use of magnification controllers position on user's hands on effectiveness, efficiency and satisfaction of accessibility tools in virtual reality. Specifically effects on magnifier tools. The previously suggested magnification tools did not leverage the 3D nature of virtual reality fully. For example, the magnifier on SeeingVR only magnifies the centre of the field of view and is fixed to the user's head. Where in our design the magnifier is attached to the user's hand which can be manipulated in 3D space without affecting the rest of the field of view. Which we suspect would enable more efficient use of a 3D medium such as virtual reality.

## Significance of the Study

This study and its results are important because Virtual Reality is a newly popularised medium and accessibility standards for people with low vision in Virtual Reality have not been created yet. This study aims to demonstrate that accessibility tools for people with low vision are useful and depending on the task the type of preferred tool differs, hence the results of this study can serve as a guideline on accessibility tool development for people with low vision.

## Research Questions

1. How does the proposed VR accessibility magnifiers compare to previously proposed accessibility magnifiers in terms of effectiveness and efficiency in enabling individuals with low vision to access virtual reality content?
2. What is the impact of the proposed VR accessibility magnifiers on the user experience and satisfaction of individuals with low vision when they use virtual reality?
3. How does fixing an accessibility magnifier to the user's hands affect the user's experience ? Does it help in leveraging the 3D nature of virtual reality ?

# Methodology & Pilot study

A virtual environment was created in Unity in order to test how well participants performed in the following tasks:

I. Menu navigation / text interaction
II. Searching
III. Shooting

In this environment, there were a total of 9 tests in 9 different rooms. 3 tests were conducted for each of the tasks listed above (in other words, 3 tests for "menu navigation / text interaction" task, 3 tests for "Searching" task and 3 tests for "Shooting" task. These tests will be detailed below under Pilot Test subsection. There were 3 different types of accessibility tools to be used in these tests (2 of them we have designed and created, one designed and analysed by the SeeingVR which we have recreated).

This study was conducted with 6 volunteers: 3 of them had low vision. Furthermore, 2 participants with low vision are university aged(18-22) and the last participant who had low vision is high school (16-18) aged. The other 3 participants do not have low vision, but they are sighted sub-nominally compared to the general populous. They have volunteered for this test of accessibility tools in VR. Moreover, the 3 participants with regular VA are university aged. 5 participants are male, and 1 participant is female.

Participants with low vision were tasked with finishing all 9 tests in 4 different ways: Once without the use of any accessibility tools, and three more times using different accessibility tools. The other 3 participants finished all 9 tests using only the tools. In each run, they used one of the tools and afterwards they evaluated it by answering the questions we have prepared for them. All tests for all participants were recorded from start to finish, and afterwards were asked a series of questions and were asked to evaluate the tools. Approximately a total of 5 hours of user testing was conducted.

## The Accessibility Tools Tested:

1) **Right-Hand Magnifie**r: When using this accessibility tool, the participants had a magnifier projector on their right wrist. This magnifier zoomed in on the location the participant's right hand is pointing at. The participant was given the ability to zoom in and out as they wished, and could turn the magnifier on and off via use of a shortcut.


Figure 2-1: Right Hand Magnifier

2) **Left-Hand Magnifier**: When using this accessibility tool, the participants had a magnifier projector on their left wrist. Contrary to Right-Hand magnifier, this magnifier does not zoom in on the direction the hand the magnifier is used at, but rather zooms in on the location the right hand is pointing at. In other words, while the magnifier display was on the left-hand, the display magnified the view in the direction of the right hand. Just like in the Right-Hand magnifier, the participant was given the ability to zoom in and out as they wished, and could turn the magnifier on and off by using the shortcuts.


Figure 2-2: Left Hand Magnifier

3) **SeeingVR Magnifier:** When using this accessibility tool, the user has a magnifier projector right in front of them, covering most of their field of vision. This was designed by SeeingVR Magnifier and was used to test the effectiveness of the tools we have developed. Just like the previous accessibility tools, the users were able to turn it on and off and zoom in and out as they wished.


Figure 2-3: SeeingVR Magnifier

The main independent statistical metric in this study is the time of completion for each test with respect to the tool used. This was calculated using Unity and was double checked manually through video recordings.

## Pilot Study:

In this study, the dependent variable is the time of completion, and the main independent variables are the tests themselves and tools used to complete tests. Time of completion is used to assess the efficiency of the system. In addition to this, in order to assess satisfaction, as indicated above, participants were asked a series of questions in order to rate the system. These findings were then used to determine the effectiveness of the project.

Participants were required to do 9 different tests with all three tools. Participants with low vision were also tasked with finishing tests without the use of any tool. Before conducting tests, participants were introduced to virtual reality and were given a very short tutorial by us on how to navigate through it. The following two subsections demonstrate how participants with low vision and participants without low vision were tested.

## Tasks in Detail:

There are three rooms for each task, each part is assigned a unique room.

**Task 1**: Menu Navigation / Text Interaction

Task 1 consists of 3 parts, in Task 1-1 the user is asked to find a button on a relatively simple menu and click on it. In Task 1-2, the user is asked a relatively hard-to-understand question and is asked to answer it. Two options are presented and both are correct. In Task 1-3, the user is asked to type their name in a virtual keyboard.

**Task 2**: Searching/Collecting in VR

Task 2 consists of 3 parts, in Task 2-1 the user is asked to find a list of 3 items in an organised room with a relatively low amount of items and put them in a bin. In Task 2-2, the user is asked to find a list of 4 items in an organised room with a relatively high amount of items and put them in a bin. In Task 2-3, the user is asked to find a list of 4 items in a cluttered room with a relatively high amount of items and put them in a bin.

**Task 3**: Shooting

Task 3 consists of 3 parts, in Task 3-1, the user is asked to shoot 4 stationary balloons, in Task 3-2, the user is asked to shoot 8 balloons moving vertically. In Task 3-3, the user is asked to shoot 7 erratically moving balloons.

An example interaction:

The user is asked to pick and use the desired accessibility tool. Afterwards:

1. In the first room (Task 1-1), the user is first presented with a menu with three buttons: They are “Main Menu”, “Options”, and “Quit”. Instruction of the task is written above the menu. The instructions ask participants to find and click on “Main Menu” button. Afterwards, the task is completed, the participant is able to see how fast they have finished their task, and are then asked to go to the second room through an anchor on the right wall.


Figure 2-4: Test 1 in Menu Navigation / Text Interaction

2. In the second room (Task 1-2), the user sees a question and two buttons. There is no right answer, when the user reads and understands the questions and picks one of the buttons the test ends. They are then asked to the third room.

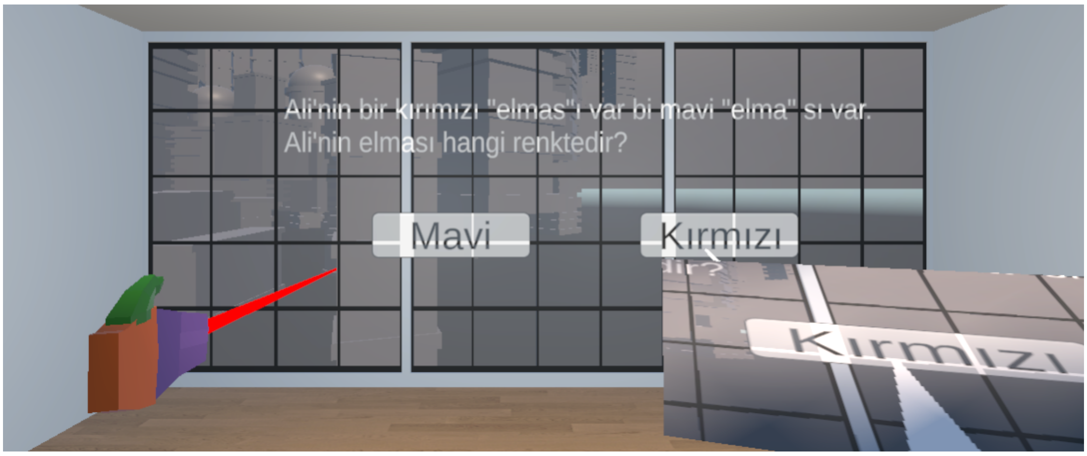


Figure 2-5: Test 2 in Menu Navigation / Text Interaction

3. In the third room (Task 1-3), the user is asked to write their name on a virtual keyboard. After they are done doing so, they are asked to go to the next room.


Figure 2-6: Test 3 in Menu Navigation / Text Interaction

4. In the fourth room (Task 2-1), the user is asked to find the indicated three items and put them in a bin as explained under Tasks subsection. Afterwards they are asked to go to the next room.


Figure 2-7: Test 1 in Searching/Collection in VR

5. In the fifth room (Task 2-2), the user is asked to find the indicated four items and put them in a bin as explained under Tasks subsection. Afterwards they are asked to go to the next room.


Figure 2-8: Test 2 in Searching/Collection in VR

6. In the sixth room (Task 2-3), the user is asked to find the indicated four items and put them in a bin as explained under Tasks subsection. Afterwards they are asked to go to the next room.

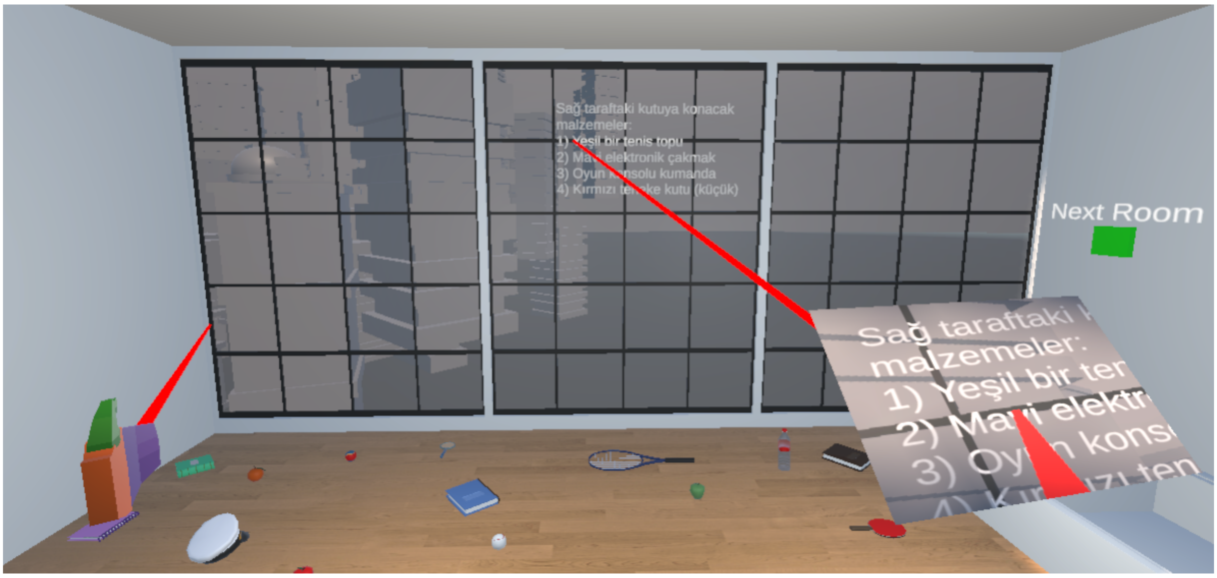


Figure 2-9: Test 3 in Searching/Collection in VR

7. In the seventh room (Task 3-1), the user is asked to pick up the gun and shoot balloons as indicated under Tasks subsection. After they are done, they are asked to go to the next room.

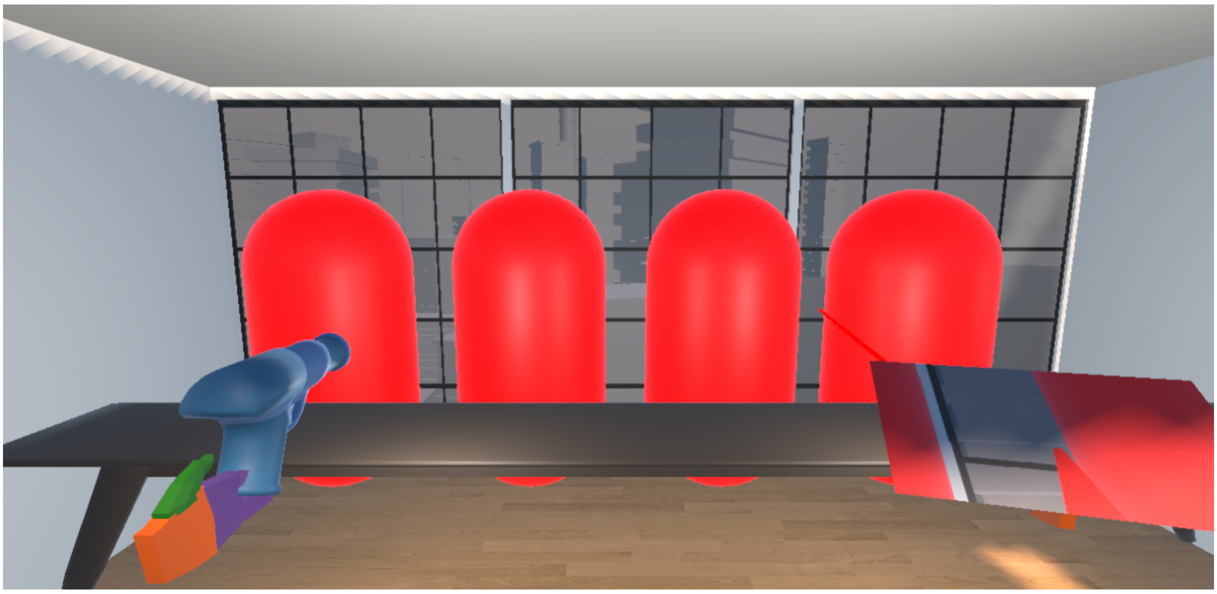

Figure 2-10: Test 1 in Shooting Task

8. In the eighth room (Task 3-2), the user is asked to pick up the gun and shoot balloons as indicated under Tasks subsection. After they are done, they are asked to go to the next room.

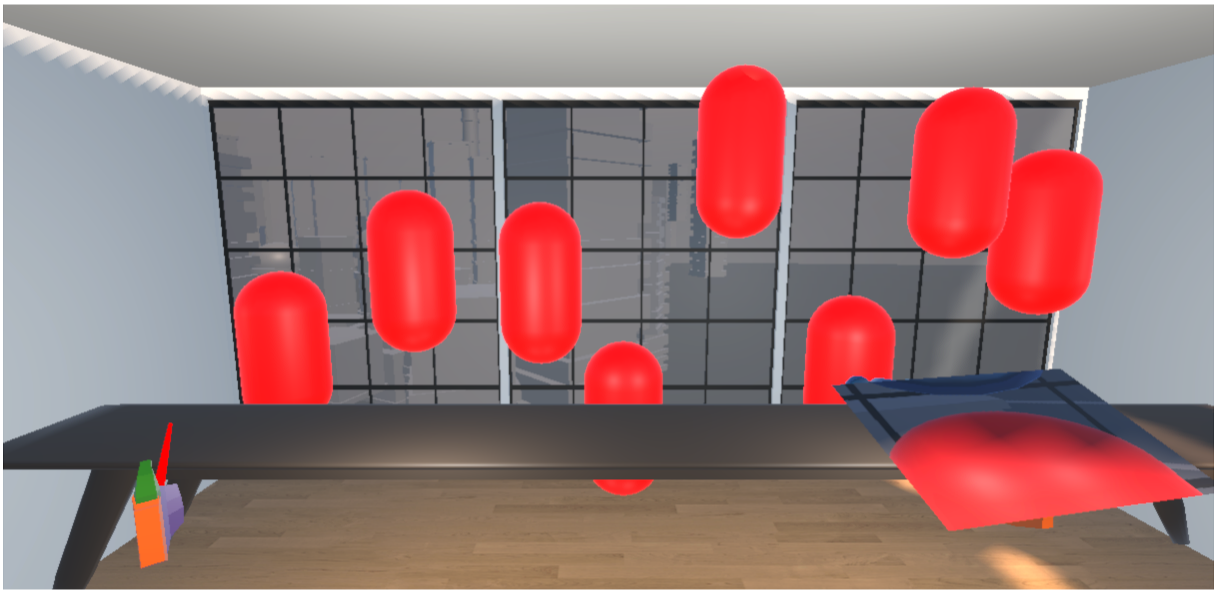

Figure 2-11: Test 2 in Shooting Task

9. In the ninth room (Task 3-3), the user is asked to pick up the gun and shoot balloons as indicated under Tasks subsection. After they are done, they are asked to go to the next room.

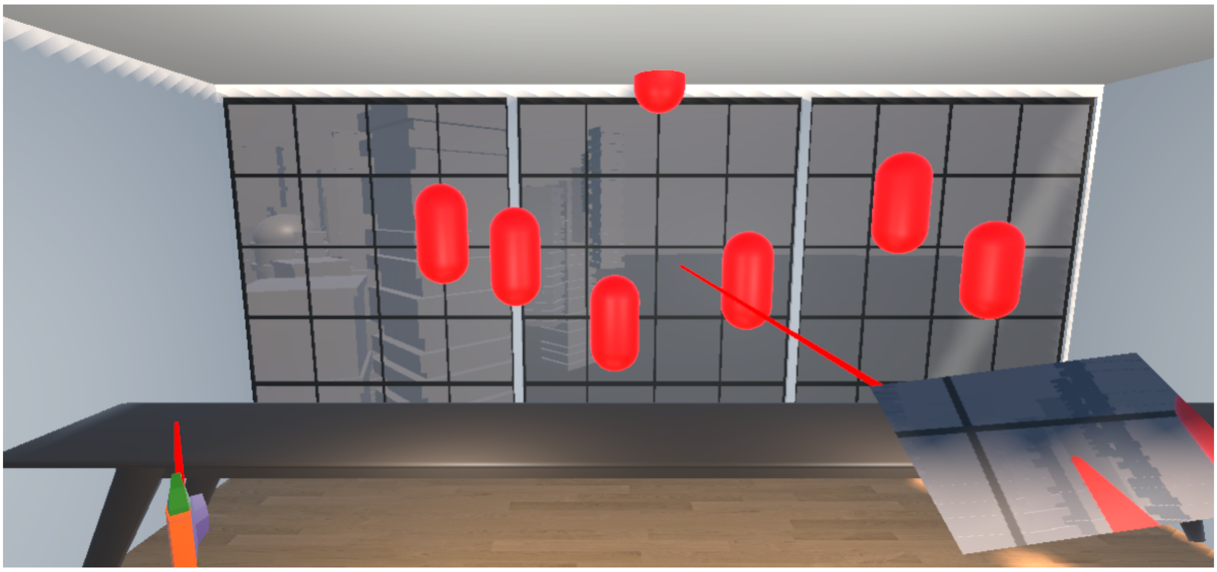

Figure 2-12: Test 3 in Shooting Task

Results are analysed with both manual analysis and Python programming language.

# Results / Analysis of Data

## Data Treatment:

Each participant participated in 9 different tests using 3 or 4 tools. Their time of completion was recorded for each test and tool; and afterwards was double checked through the videos. The completion time of tests were then recorded into an excel file and were then imported into a jupyter notebook for data visualisation and analysis. For each participant with low vision, a total of 36 data points, and for each participant without low vision a total of 27 data points were recorded; making a total of 225 data points. In this section the results will be demonstrated.

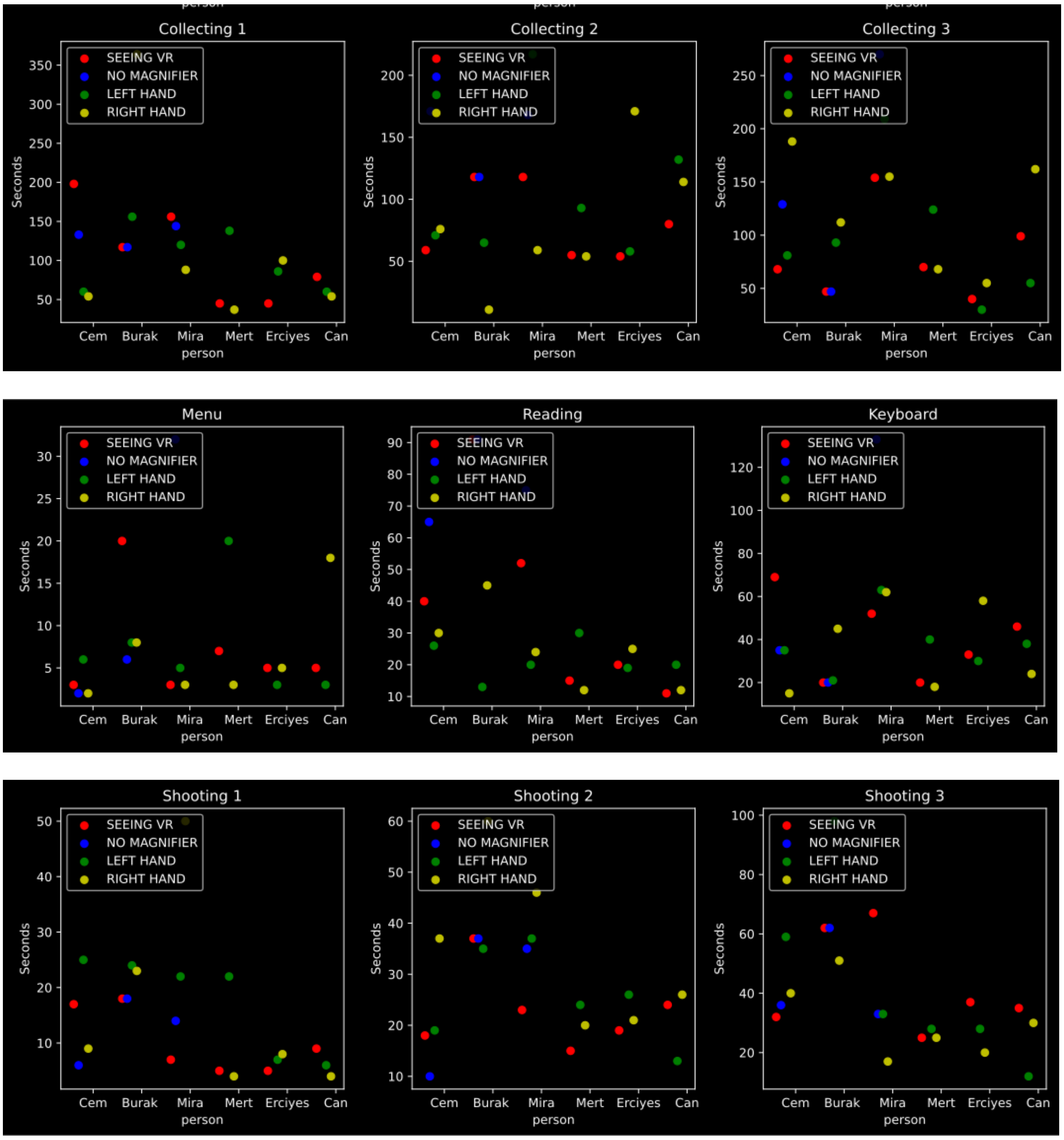


Figure 3-1: Time of Completion for Each Test

Figure 3-1 represents the overall data points recorded throughout the study, there are a total of 9 tests. The type of tool used is colour coded and is shown in a clustered manner on top of the participant's name. This data will be analysed in order to draw conclusions as to how our prototype performed in terms of efficiency, effectiveness, and satisfaction.

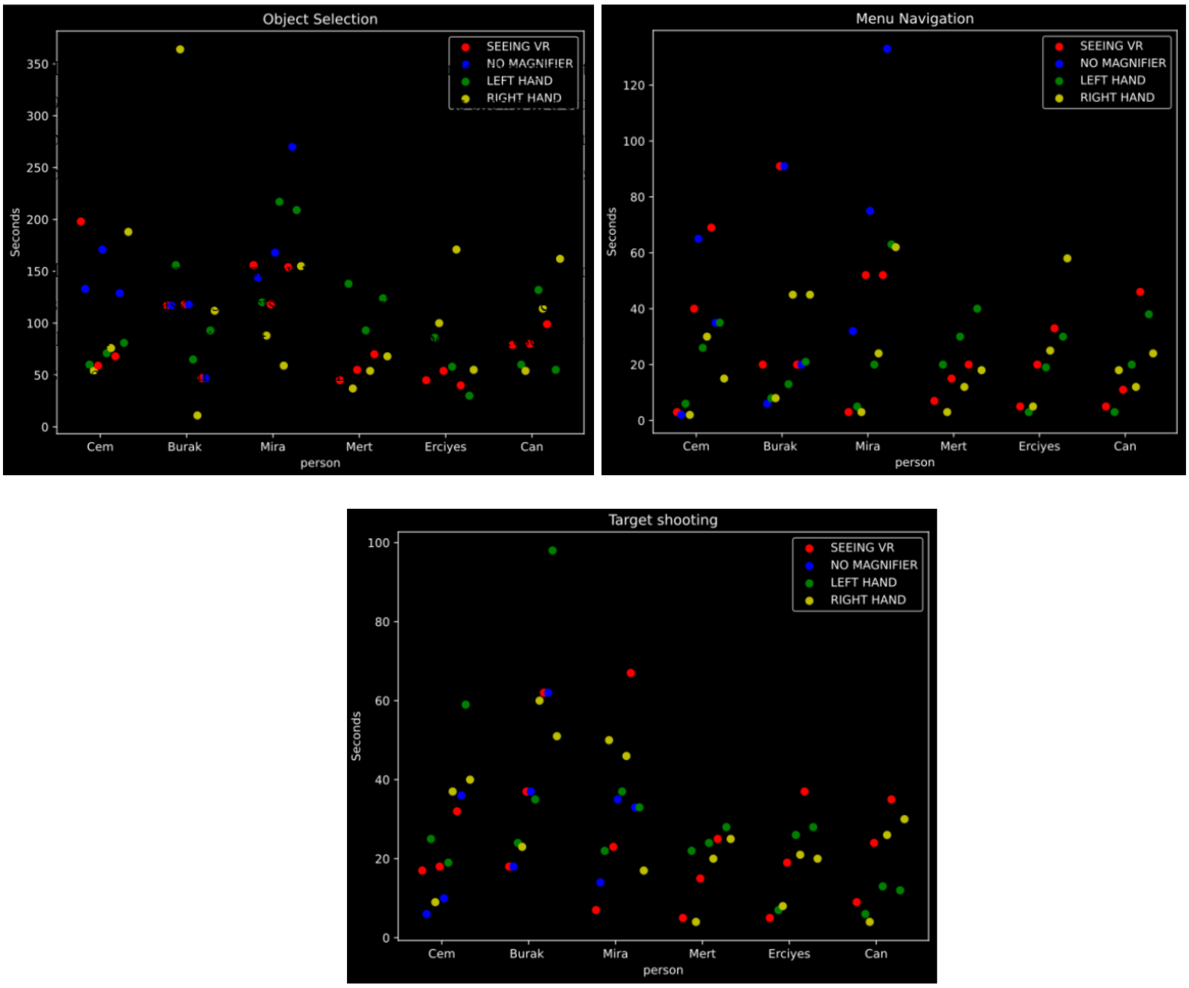


Figure 3-2: Time of Completion for Each Test Categorised with Respect to Tasks

The plots above categorise tests by the tasks they are a part of. As mentioned in the Methodology section each task has 3 tests associated with them hence there are three plots. For each task there are 12 to 16 different points, all of these points represent the time of completion for the sub-tests participants had to perform. While this is a comprehensive way to visualise data, by itself it is hard to draw conclusions, following graphs and statistical tests under Statistics subsection will be focusing on that.

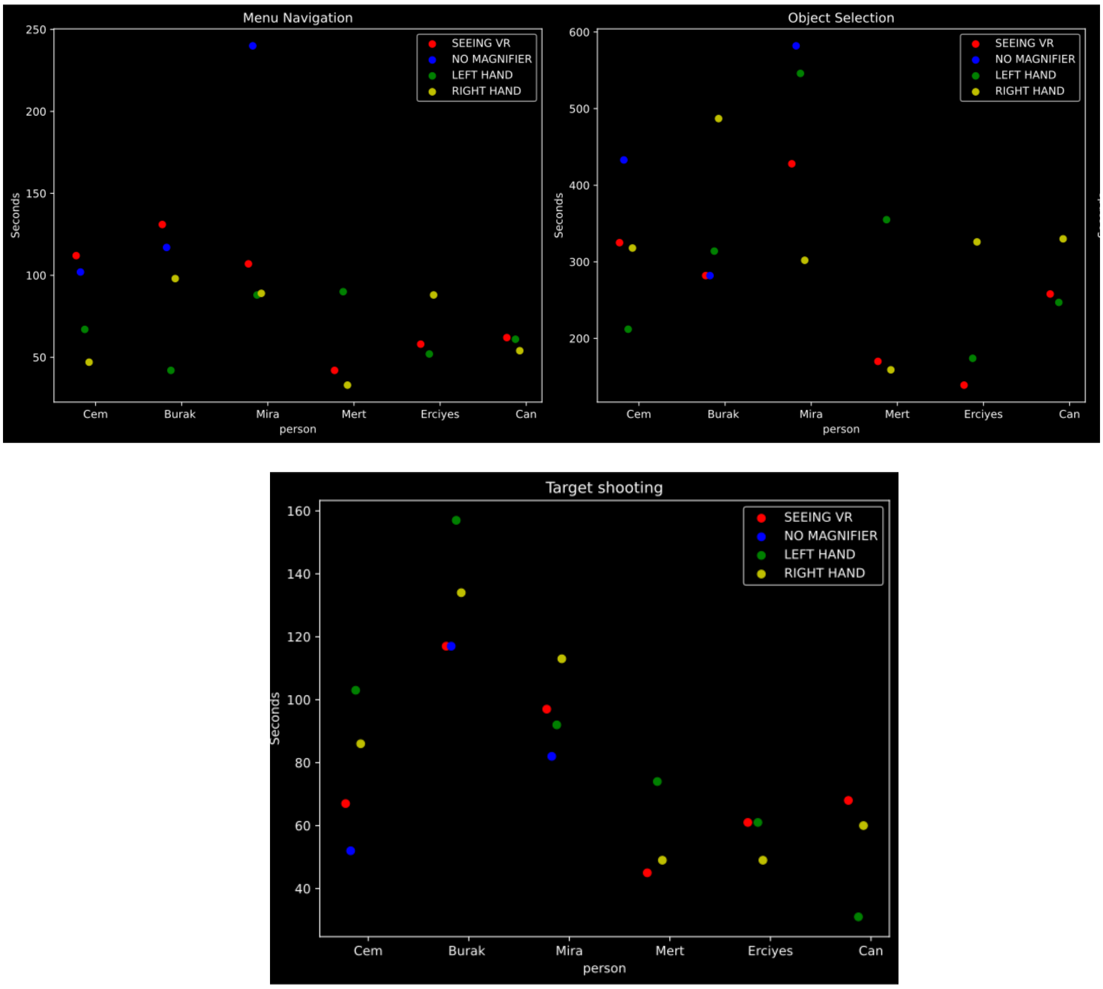


Figure 3-3: Total Time Spent for Each Task

The plots above categorise tests by the tasks they represent just like the previous set of plots, however for each tool there is one data point per user. This visualisation gives a better understanding of how different tools performed with respect to Tasks.

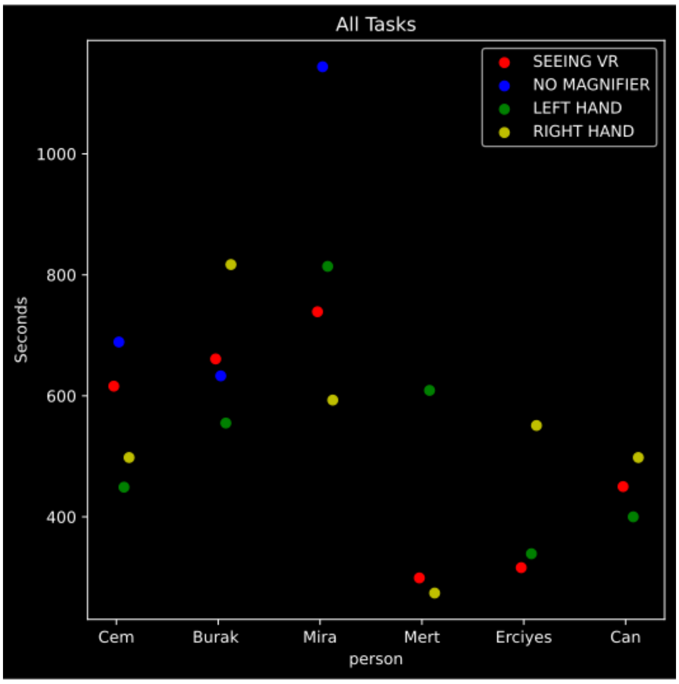


Figure 3-4: Total Time Spent for Each Task Categorised with Respect to Participants

The plot above represents the total amount of time each participant spends on each task, the data points are addition of the three subtests relative to their tasks. For 2 out of 3 of our low vision participants the time of completion for each task was longest for No Magnifier tests. The fact that this was not the case for one of the low vision participants was rather surprising. We believe this is due to errors during measure of completion time and experimentation setup, since during the interview the participant himself mentioned he had the hardest time when trying to finish tasks without using any accessibility tools. As for tools, the visuals indicate there is no overall best accessibility tool for this test setup, this will be statistically demonstrated below the Statistic subsection.

## Verbal Data:

During the tasks every participant was asked to verbally describe their experience and at the end of the tests every participant was interviewed. These sessions were recorded and transcribed. The results and common trends amongst participants are explained below.

In addition to quantitative data, qualitative data was also collected during and after the tests. Each participant was asked what they thought about different tools. First of all, all of our low vision participants mentioned that magnifier tools were a huge help when navigating through tasks, that they were not able to complete some tasks outside of the testing without the use of any accessibility tools. Furthermore, even though the tasks were accomplishable the existence of a magnifier reduced the cognitive load during the execution of the task. For example participant burak could read task 1.2 by walking and teleporting from word to word he had to remember the previous chunks in their mind to understand the whole sentence.

For tools themselves, all of our participants mentioned that right hand and left hand magnifiers were more convenient for menu navigation and text interaction. They mentioned SeeingVR was relatively inconvenient to use for text interaction since it requires precise neck movement to change the direction of magnification in contrast to hand magnifiers where the participant only has to move their hand to change the direction. For Searching Task, participants mentioned that while magnifiers were useful for checking the colour and shape of an object far away, they were not particularly useful when grabbing and putting the object in the desired position.

The participants also mentioned hand magnifiers, especially the left hand magnifier was not very convenient for grab and throw operations since the participant has no way of conveniently accessing the magnifier when using the hand with the magnifier direction to grab and throw. Finally, as for Target Shooting, they mentioned SeeingVR was the most useful since the magnification projector was in front of their faces they were able to use their hands more freely. Also, some of the participants have found the left hand magnifier very cognitively demanding during regular use.

# Descriptive Statistics:

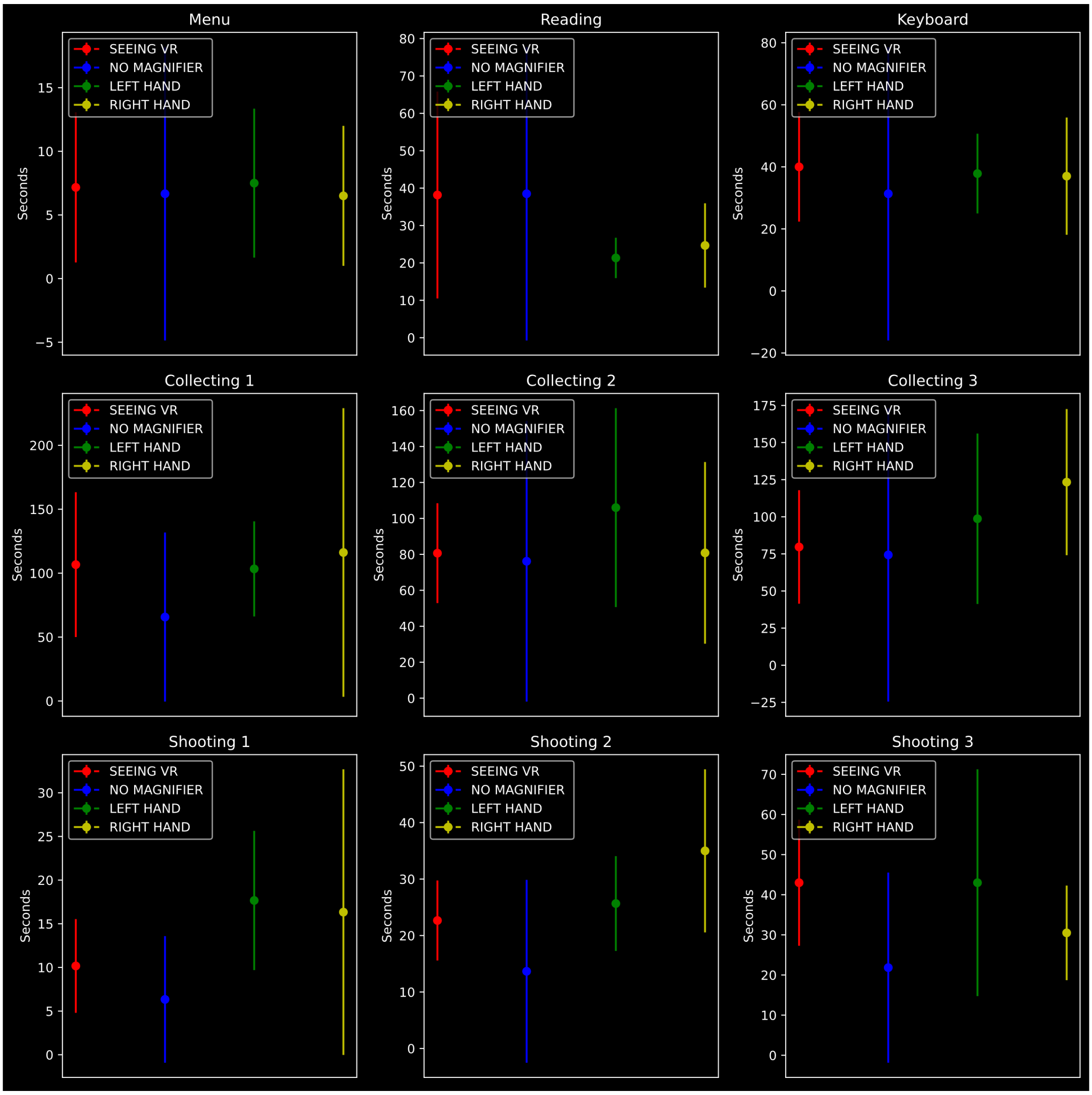


Figure 3-5: Error Charts for Each Test with Respect to Tools Used

Per task mean and standard deviation can be seen in the figure above.

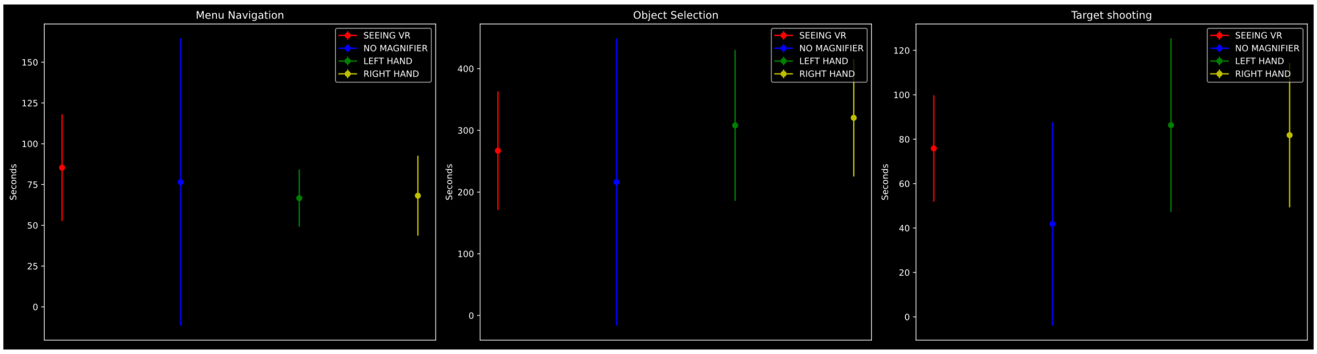


Figure 3-6: Error Charts for Each Task with Respect to Tools Used

The mean and the standard deviation of the aggregated subtasks can be seen in the figure above.

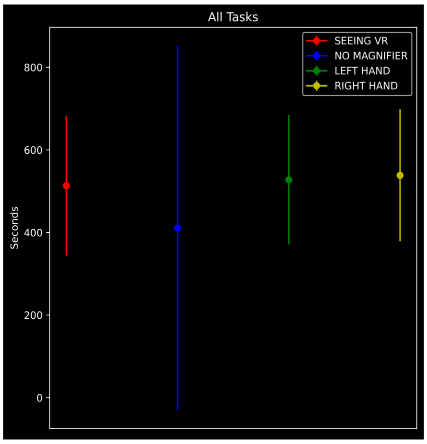


Figure 3-7: Error Chart for All Tasks with Respect to Tools Used

Total mean and standard deviation can be seen in the figure above.

# Inferential Statistics:

The tables below list all of our T-tests. The text on green rows represents the tests. We have performed our T-tests on all dual combinations of tools for each test in order to see if there were significant differences in our population distributions, which in this case entail the time of completion for each with each tool. We have conducted a total of 72 t-tests and they are all listed below. Amongst all of our T-tests, 2 of them demonstrated statistically significant differences between population distributions. They are explained in detail below.

T tests :

| Name | T value | P value | Name | T value | P value |
|---|---|---|---|---|---|
| Menu | | | Collecting 2 | | |
| SEEING VR vs NO MAGNIFIER | 0.086 | 0.933 | SEEING VR vs NO MAGNIFIER | 0.121 | 0.906 |
| SEEING VR vs LEFT HAND | -0.090 | 0.930 | SEEING VR vs LEFT HAND | -0.915 | 0.382 |
| SEEING VR vs RIGHT HAND | 0.185 | 0.857 | SEEING VR vs RIGHT HAND | -0.006 | 0.995 |
| NO MAGNIFIER vs LEFT HAND | -0.144 | 0.888 | NO MAGNIFIER vs LEFT HAND | -0.697 | 0.502 |
| NO MAGNIFIER vs RIGHT HAND | 0.029 | 0.977 | NO MAGNIFIER vs RIGHT HAND | -0.112 | 0.913 |
| LEFT HAND vs RIGHT HAND | 0.278 | 0.786 | LEFT HAND vs RIGHT HAND | 0.751 | 0.470 |
| Reading | | | Collecting 3 | | |
| SEEING VR vs NO MAGNIFIER | -0.016 | 0.988 | SEEING VR vs NO MAGNIFIER | 0.113 | 0.913 |
| SEEING VR vs LEFT HAND | 1.336 | 0.211 | SEEING VR vs LEFT HAND | -0.616 | 0.552 |
| SEEING VR vs RIGHT HAND | 1.011 | 0.336 | SEEING VR vs RIGHT HAND | -1.567 | 0.148 |
| NO MAGNIFIER vs LEFT HAND | 0.969 | 0.355 | NO MAGNIFIER vs LEFT HAND | -0.476 | 0.644 |
| NO MAGNIFIER vs RIGHT HAND | 0.758 | 0.466 | NO MAGNIFIER vs RIGHT HAND | -0.992 | 0.344 |
| LEFT HAND vs RIGHT HAND | -0.596 | 0.564 | LEFT HAND vs RIGHT HAND | -0.729 | 0.483 |
| Keyboard | | | Shooting 1 | | |
| SEEING VR vs NO MAGNIFIER | 0.384 | 0.709 | SEEING VR vs NO MAGNIFIER | 0.950 | 0.364 |
| SEEING VR vs LEFT HAND | 0.222 | 0.829 | SEEING VR vs LEFT HAND | -1.745 | 0.112 |
| SEEING VR vs RIGHT HAND | 0.259 | 0.801 | SEEING VR vs RIGHT HAND | -0.801 | 0.442 |
| NO MAGNIFIER vs LEFT HAND | -0.297 | 0.773 | NO MAGNIFIER vs LEFT HAND | -2.352 | 0.041 |
| NO MAGNIFIER vs RIGHT HAND | -0.249 | 0.809 | NO MAGNIFIER vs RIGHT HAND | -1.250 | 0.240 |
| LEFT HAND vs RIGHT HAND | 0.082 | 0.937 | LEFT HAND vs RIGHT HAND | 0.164 | 0.873 |

| Collecting 1 | | | Shooting 2 | | |
|---|---|---|---|---|---|
| SEEING VR vs NO MAGNIFIER | 1.053 | 0.317 | SEEING VR vs NO MAGNIFIER | 1.139 | 0.281 |
| SEEING VR vs LEFT HAND | 0.110 | 0.915 | SEEING VR vs LEFT HAND | -0.610 | 0.555 |
| SEEING VR vs RIGHT HAND | -0.168 | 0.870 | SEEING VR vs RIGHT HAND | -1.714 | 0.117 |
| NO MAGNIFIER vs LEFT HAND | -1.110 | 0.293 | NO MAGNIFIER vs LEFT HAND | -1.471 | 0.172 |
| NO MAGNIFIER vs RIGHT HAND | -0.863 | 0.408 | NO MAGNIFIER vs RIGHT HAND | -2.198 | 0.052 |
| LEFT HAND vs RIGHT HAND | -0.241 | 0.814 | LEFT HAND vs RIGHT HAND | -1.249 | 0.240 |

| Shooting 3 | | |
|---|---|---|
| SEEING VR vs NO MAGNIFIER | 1.665 | 0.127 |
| SEEING VR vs LEFT HAND | 0.000 | 1.000 |
| SEEING VR vs RIGHT HAND | 1.423 | 0.185 |
| NO MAGNIFIER vs LEFT HAND | -1.283 | 0.228 |
| NO MAGNIFIER vs RIGHT HAND | -0.732 | 0.481 |
| LEFT HAND vs RIGHT HAND | 0.913 | 0.383 |

Statistically significant differences were

In Shooting 1, NO MAGNIFIER compared to LEFT HAND had a t value of -2.352 with p value of 0.041 which makes the finding statistically significant and indicates that the left hand magnifier is superior to using no magnifier.

In Shooting 2, NO MAGNIFIER compared to RIGHT HAND had a t value of -2.198 with p value of 0.052 which makes the difference pretty close to a statistically significant delta. However, it misses the threshold. Furthermore, given the large number of comparisons such a difference is expected and might be the result of sampling fluke. This notion is further reinforced with analysis of aggregated data where this delta diminishes even further.

| Name | T value | P value | Name | T value | P value |
|---|---|---|---|---|---|
| Menu Navigation | | | Object Selection | | |
| SEEING VR vs NO MAGNIFIER | 0.210 | 0.838 | SEEING VR vs NO MAGNIFIER | 0.451 | 0.661 |
| SEEING VR vs LEFT HAND | 1.123 | 0.288 | SEEING VR vs LEFT HAND | -0.589 | 0.569 |
| SEEING VR vs RIGHT HAND | 0.938 | 0.370 | SEEING VR vs RIGHT HAND | -0.882 | 0.398 |
| NO MAGNIFIER vs LEFT HAND | 0.245 | 0.812 | NO MAGNIFIER vs LEFT HAND | -0.781 | 0.453 |
| NO MAGNIFIER vs RIGHT HAND | 0.204 | 0.843 | NO MAGNIFIER vs RIGHT HAND | -0.926 | 0.376 |
| LEFT HAND vs RIGHT HAND | -0.111 | 0.914 | LEFT HAND vs RIGHT HAND | -0.178 | 0.862 |
| Target shooting | | | | | |
| SEEING VR vs NO MAGNIFIER | 1.469 | 0.173 | | | |
| SEEING VR vs LEFT HAND | -0.512 | 0.620 | | | |
| SEEING VR vs RIGHT HAND | -0.332 | 0.747 | | | |
| NO MAGNIFIER vs LEFT HAND | -1.652 | 0.130 | | | |
| NO MAGNIFIER vs RIGHT HAND | -1.591 | 0.143 | | | |
| LEFT HAND vs RIGHT HAND | 0.198 | 0.847 | | | |

These tests show that for a significance value of 0.05, most of our population distributions don't indicate significant change when different tools are used. However, due to differences in the results of our inferential statistics and user-based qualitative-data, we believe further testing with a more established larger test group is necessary to draw stronger conclusions. This will be explained in detail under Discussions section

## Summary of the Results:

There was no clear overall successful accessibility tool amongst the accessibility tools tested in this research. However, all of our lower vision participants claimed the tests they were given would have been much harder to accomplish without the use of accessibility tools. Participants have claimed different tools were good for different tasks as mentioned above in qualitative data analysis. They have also claimed these tools increased their satisfaction of Virtual Reality experience. For instance they did not have to walk or teleport to objects of interest to use the system and this facilitated their decision making process in VR.

# Discussion and Conclusion

There were several limitations while conducting the study. One of the limitations was the number of participants available. Originally, we planned 4 participants with low vision for testing the left/right magnifier and SeeingVR. However, one of the participants could not join the test due to medical reasons. Moreover, we tried to reach other low vision participants via email and other auxiliary channels however no one responded; therefore, for future studies, a more established participant group in order to increase test data would make this study more conclusive. Due to difficulties when finding participants with low vision, we have also included participants without low vision in order to compare them, further increasing the scope of the study. In addition to this, our participants without low vision had near-sightedness and they also indicated that tested accessibility tools were useful to them in certain situations.

Our data collection methods for time stamps were also relatively lacking. We recorded the time of completion in our unity application and recorded the videos about participants' tests to find time of completion for each test. However, due to lack of visual cues in our tests, through recordings we could not pinpoint some of the participants' time of completion time, for instance at object collection/search tests since there is no notification sound for putting an object into the target area at VR. Contrary to this, in Shooting Task, the dart gun had a sound that allowed us to easily determine the starting and finishing time of each shooting test.

The third limitation is about test designs. Some candidates stated that some accessibility tests are too accessible. For instance, the menu in the menu navigation task was too big, not representing actual menus in VR applications which are much smaller. Further tests should focus on real life applications of tasks more when tests are being designed so that results of tests represent how a user might perform in a real world situation.

The last limitation was the lack of test variety for different tools. Each user has tried multiple tools over the same 9 tests, this caused them to get faster with each iteration as they memorised tasks. To avoid the effects of these we have randomised the used tools in order to negate the effects of this in our results. However given the sample size this was not effective enough. In future tests, this should be considered when tests are being designed.

Regardless of the limitations of the study, our findings clearly indicate that accessibility tools are of great importance for people with low vision, not contrary to findings of previous research mentioned under the literature review section. Our prototypes build up on previous studies as well. For instance, in SeeingVR, their magnification lens as mentioned above stays right in front of the user and was not deemed very useful when searching. The magnification controllers we have developed allowed users to have more fine control over the magnified projection and they claimed this allowed them to check objects in the distance with minimal movement without moving their heads like they had to in SeeingVR, making the whole search process more satisfactory.

The results of this study demonstrate that accessibility tools for VR can be effective.

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# Appendix

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